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Design of Experiment Methods in High Speed Signal Via Transition in Printed Circuit Board

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Abstract- With increase in data transfer speeds between integrated circuits, memories and connectors, the interconnects in printed circuit boards require careful design and optimization. A critical part of an interconnect is via transition. To meet the design goals and maintain signal integrity, every part of the interconnect needs to be carefully designed. Designing via involves variation of several parameters and it is extremely important to understand their contribution to find the usable parameters yielding best possible performance. Out of these numerous combinations of parameters, Design of Experiments (DOE) can offer much needed understanding, suggest possible values and speed up the design process. In this manuscript, two DOE methods (Box-Behnken Design and Central Composite Design) are used to understand the behavior of a pair of vias operating in differential mode.

Keywords – Design of Experiment, Signal Integrity, Via Modeling, Differential Via, Electromagnetic Modeling of Via.

I. INTRODUCTION

With new data transmission standards being introduced [1], designers are paying careful attention to the interconnects to meet the design goals. Transmission traces are easier to synthesize, when compared to via transitions. Routing of traces are highly automated when state-of-the art layout tools are utilized. In printed circuit boards, via transitions is an essential part as it bridges between layers and accomplishes the routing between desired points. However, designing a good via transition is still a challenge. A careful design of a via and its return path is extremely important as this can cause significant change in the final signal quality [2]. A via is a discontinuity in impedance of the signal route. Therefore, even if the signal lines are well-designed, via transition can be the bottle neck in the end-to-end signal integrity. Therefore, significant efforts are spent in designing the optimum via transition that will offer best performance during operation [3]. There are many manufacturing restrictions that also dictate the values that are acceptable in final design. This requires the designer to optimize many parameters and arrive at the final decision [4]. Due to numerous possible combinations, fabrication and measurement of hundreds of combinations is not practical due to limited resources: i.e. engineering efforts, cost of manufacturing, testing and time. In that regard, electromagnetic simulation (EM) tools can offer much needed insight without fabrication and measurement.

However, EM simulation with high accuracy is computationally costly and time consuming. Therefore, running simulations for all possible combinations is not a preferred option. In their groundbreaking work, Sacks, *et al.* presented how number of simulation (at their 1989 publication, it was termed “Computer Experiments”) runs can be reduced while achieving the required information about possible results for all possible variations [5]. In electronic design and EM modeling, Design of Experiments (DOE) allows designer to selectively pick combinations and create possible outcomes that covers possible variations, saves design time and accelerates workflow. DOE also allows designer to find the significance or sensitivity of one variable by illustrating the direct impact on the result due to changes in that specific variable. In this article, two DOE methods will be studied using Finite-Element Method (FEM) based EM simulator, and comparison between methods will be presented. The DOE methods used in this simulation experiment are: Box-Behnken Design and Central Composite Design.

II. BRIEF DESCRIPTION OF DESIGN OF EXPERIMENT METHODS

Most of the times, the outcomes of a variable changes are not linear over the range of its own variation. It is simpler to vary one variable at a time and obtain its curve fitting using interpolation methods. However, a multi-variable problem presents a much bigger challenge that is better handled by Design of Experiment. Since its early introduction in [5], many methods and algorithms have been developed for DOE. By providing statistical basis for the inputs, the output predication mechanism becomes efficient. The Response Surface Methodology (RSM) aims at finding a surface that presents the results for possible combination by employing the higher order impacts. Therefore, a curved response can be interpreted easily to trace the contributors to a specific output. These two methods are described briefly in the following sub-sections.

2.1 Box-Behnken Design –

Originally presented in 1960 [6], Box-Behnken Design (BBD) uses midpoints of the edges of the experimental values. Compared to Central Composite Design, Box-Behnken Design may have fewer design points for the same number of variables, is less computationally expensive which allows faster completion of DOE simulations. Therefore, BBD is popular in solving problem as it is more efficient in tackling problems with higher number of variables [7]. It also is becoming more prolific in recent publications [8].

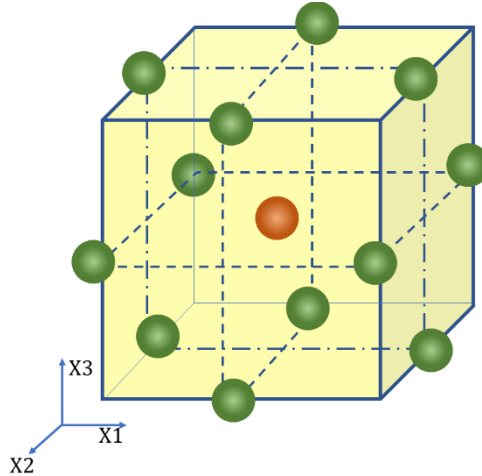


Figure 1. Box-Behnken Design has emphasis on mid-points

2.2 Central Composite Design –

Central Composite Design (CCD) method of DOE begins with factorial experiments. The median values are used as the inputs to determine the set of center points. The subsequent runs are similar to the center point experiment with the exception of one factor or variable that will assume other values, and often they may be higher and lower than the defined range. These points are known as axial points. Due to their placements, these axial points are also called star points. A special case of CCD is known as Face-Centered Design (FCD) where the axial or star points are on the face of the factorials. Fig. 2 shows how the center points and axial points are located in terms of relative values. Another key difference between Box-Behnken Design and Central Composite Design is the feasibility of using the solution. Since Central Composite Design may pick values outside the factorial limits, some of its outputs may not be suitable for manufacturing.

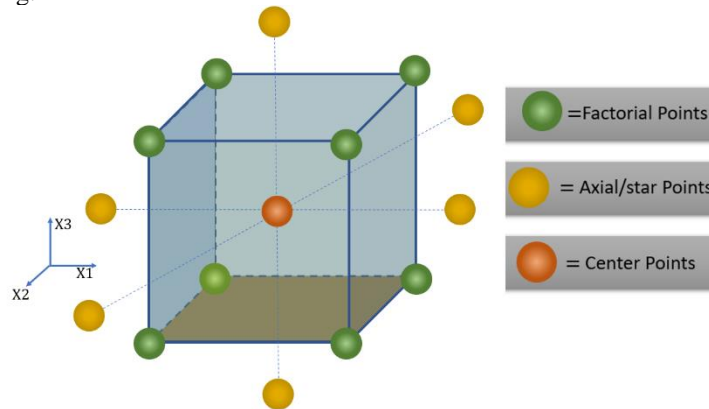


Figure 2. Simplified presentation of locations of values for Central Composite Design

On the other hand, Box-Behnken Design picks values that are always within provided constraints, and always within the manufacturable limit. To overcome this, some algorithms force CCD to follow some boundary. When, to ensure manufacturability, the axial values of CCD are picked on the face of the factorials space, this becomes Face-Centered Design (FCD).

III. VIA DESIGN FOR OPERATION IN DIFFERENTIAL MODE

Differential vias are popular because this configuration offers many advantages over their single ended counterpart. Due to different nature of electricity flow and possible couplings, the design approach is different from the single ended via. In addition to few common parameters (e.g. hole size, anti-pad size, etc.) of single ended via, the design of differential via brings in few more design variables (e.g. distance between the holes, trace bending angle, etc.). The use of DOE is a powerful tool to handle these extra variables. In this experiment, differential via transitions (for differential mode) between two microstripline lines are considered. Three variables that are studied here are: via anti-pad, via radius (half of via diameter) and spacing between vias. Figure 3 shows a via transition between top and bottom layers.

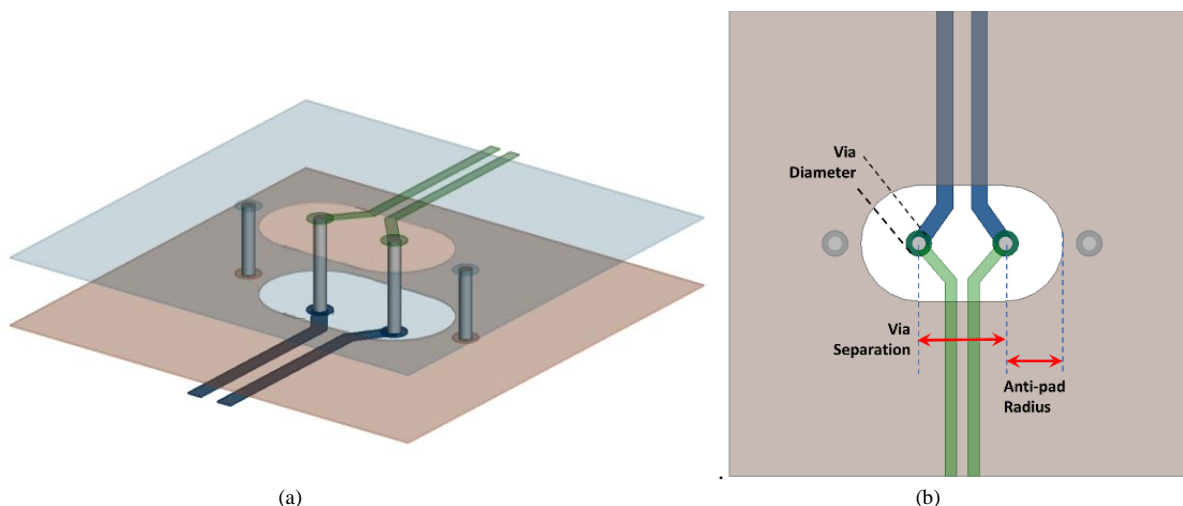


Figure 3. Via for differential mode (a) Microstripline lines and vias (b) different variable marked in top view.

In printed circuit board (PCB) manufacturing, the unit 'mil' is still commonly used. 1 mil is equal to 0.001 inch. In metric system, 1 mil=0.0254 milli-meter. For this simulation, a pair of microstrip lines and its ground plane, pair of via transitions, and then on the other side another pair of lines and its ground plane are considered with substrate with $\epsilon_0=4.4$. After the scattering matrix (s-parameter) is obtained via Finite Element Method (FEM) based electromagnetic (EM) simulation tool, the result is post processed to obtain differential matrix for finding out differential insertion loss and differential return loss. The following ranges are defined for consideration:

Table -1 Parameters and their ranges of variation

Parameter Name	Lowest Value (mil)	Highest Value (mil)
Via Radius (half of Via diameter)	1.45	4.35
Separation between Vias	20	60
Anti-Pad Size	25	50

A commonly used metric for performance in frequency domain is scattering parameters (s-parameters). A simple definition of s-parameter (single ended) is:

$$S_{ij} = \frac{V_i^-}{V_j^+} \quad (1)$$

S_{ij} is calculated this way when a port j is driven with incident voltage of V_j^+ and the voltage at port i is V_i^- . This has a condition that all other ports are terminated with a matched load, and nothing is reflected back from the rest of the network [9]. When $i = j$, it is return loss, and when $i \neq j$, it is insertion loss. From initial extraction, it is possible to calculate the mixed mode (differential mode and common mode) s-parameters from single-ended s-parameters. For this structure, there are 4 ports and it would yield a 4×4 scattering matrix with S_{ij} having combinations of $i = 1,2,3,4$ and $j = 1,2,3,4$. In this case, the differential mode s-parameters are of interest and their definitions are provided below:

$$S_{dd11} = \frac{S_{11} - S_{21} - S_{12} + S_{22}}{2} \quad (2)$$

$$S_{dd21} = \frac{S_{31} - S_{32} - S_{41} + S_{42}}{2} \quad (3)$$

IV. RESULTS AND ANALYSIS

The results are presented for both methods of DOE. To achieve similar behavior, same computing resources are used for both methods. The findings are presented in the respective sub-sections below:

4.1 Box-Behnken Design –

For Box-Behnken Design, 13 combinations are picked and simulated. The results for Sdd11 and Sdd21 are presented in below table for highest frequency of 20GHz:

Table -2 Parameters, their values for BBD and outputs due these values at 20GHz

Exp no.	Anti-pad (mil)	Via Radius (mil)	Via Separation (mil)	Sdd21 (dB)	Sdd11 (dB)
1	37.5	2.9	40	-1.506	-7.212
2	25	1.45	40	-0.501	-20.633
3	50	1.45	40	-1.030	-10.176
4	25	4.35	40	-0.573	-18.262
5	50	4.35	40	-1.038	-9.280
6	25	2.9	20	-1.969	-5.849
7	50	2.9	20	-1.039	-9.477
8	25	2.9	60	-0.467	-30.145
9	50	2.9	60	-0.863	-11.681
10	37.5	1.45	20	-1.802	-6.095
11	37.5	4.35	20	-0.559	-16.063
12	37.5	1.45	60	-1.397	-7.741
13	37.5	4.35	60	-0.757	-12.255

Once the results are available from Box-Behnken Design, a specific combination can be applied, and results can be observed. Values for Sdd21 is preferred to be near zero (largest among negative numbers), and for Sdd11 is preferred to be away from zero (smallest among negative numbers) For this via transition, the best case is #8 (largest Sdd21 and smallest Sdd11), and worst case is #6 (smallest Sdd21 and largest Sdd11). They are plotted below:

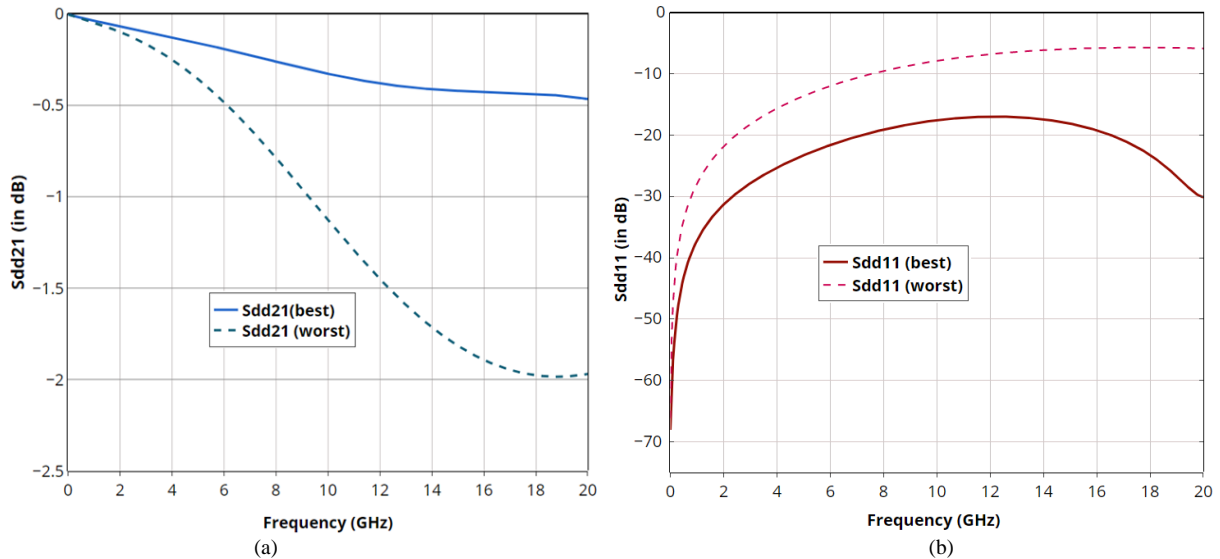


Figure 4. Differential mode parameters of the via in best and worst cases found in BBD (a) Insertion loss, Sdd21; (b) Reflection loss Sdd11

The response surface can be observed for all the combinations of the parameters. Two combinations generate the surface while another one is kept fixed, and they can switch places as long as any one of them is fixed. For example, the following response surface is generated for via separation of 1.016mm (40 mil):

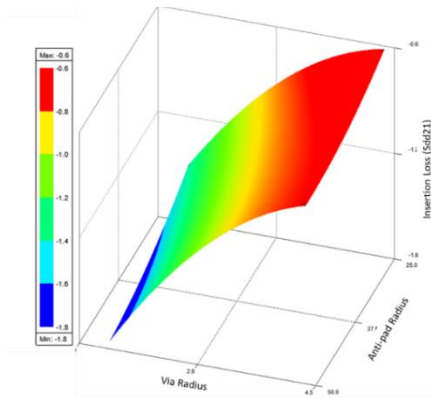


Figure 5. Response surface of Box-Behnken Design for differential mode via. (anti-pad radius and via radius are in mil, and Insertion loss is in dB)

The other crucial information is the sensitivity, i.e. how the changes in input affect the output. Near the mid-point of the parameters, the following sensitivity is observed.

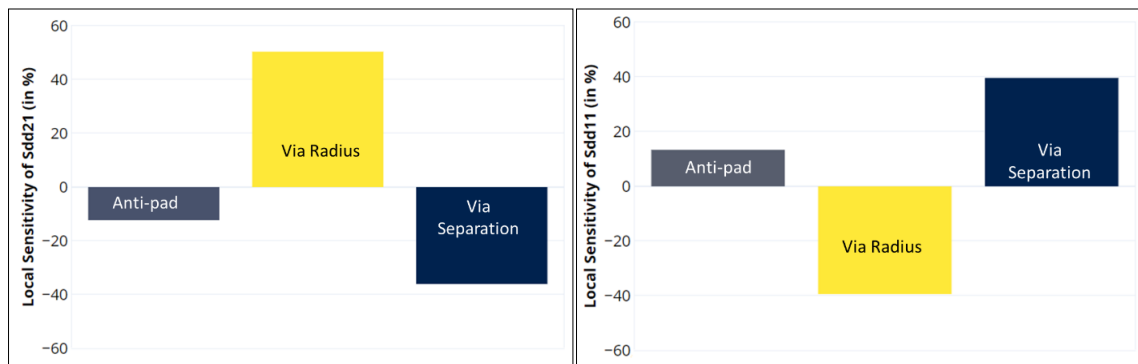


Figure 6. Relative sensitivity in Sdd21 and Sdd11 due to anti-pad, via radius and via separation

4.2 Central Composite Design –

The CCD begins with 15 combinations for 3 parameters. The combinations and the results for Sdd11 and Sdd21 are presented in below table for highest frequency of 20GHz:

Table -3 Parameters, their values for CCD and outputs due these values at 20GHz

Exp no.	Anti-pad (mil)	Via Radius (mil)	Via Separation (mil)	Sdd21 (dB)	Sdd11 (dB)
1	25	1.45	20	-0.892	-10.554
2	25	1.45	60	-1.702	-6.747
3	25	2.9	40	-0.841	-11.533
4	25	4.35	20	-0.532	-19.284
5	25	4.35	60	-0.681	-15.781
6	37.5	1.45	40	-1.712	-6.411
7	37.5	2.9	20	-0.569	-15.939
8	37.5	2.9	40	-1.039	-9.477
9	37.5	2.9	60	-1.268	-8.379
10	37.5	4.35	40	-0.689	-13.562
11	50	1.45	20	-1.071	-9.000
12	50	1.45	60	-2.038	-5.647
13	50	2.9	40	-1.134	-8.769
14	50	4.35	20	-0.457	-42.817
15	50	4.35	60	-0.954	-10.737

For this via transition, the best case is #14 (largest Sdd21 and smallest Sdd11), and worst case is #12 (smallest Sdd21 and largest Sdd11). For illustrative purpose, they are plotted in Fig. 7.

Sensitivities on Sdd11 and Sdd21, similar to that of Box-Behnken Design, are also obtained from Central Composite Design. The impacts of the variables are similar i.e. via radius shows positive correlation with Sdd21 and negative correlation with Sdd11. The other two also showed the same trend. In order to avoid repetition of too similar results, the sensitivity plots for CCD are not included in this manuscript for keeping it concise.

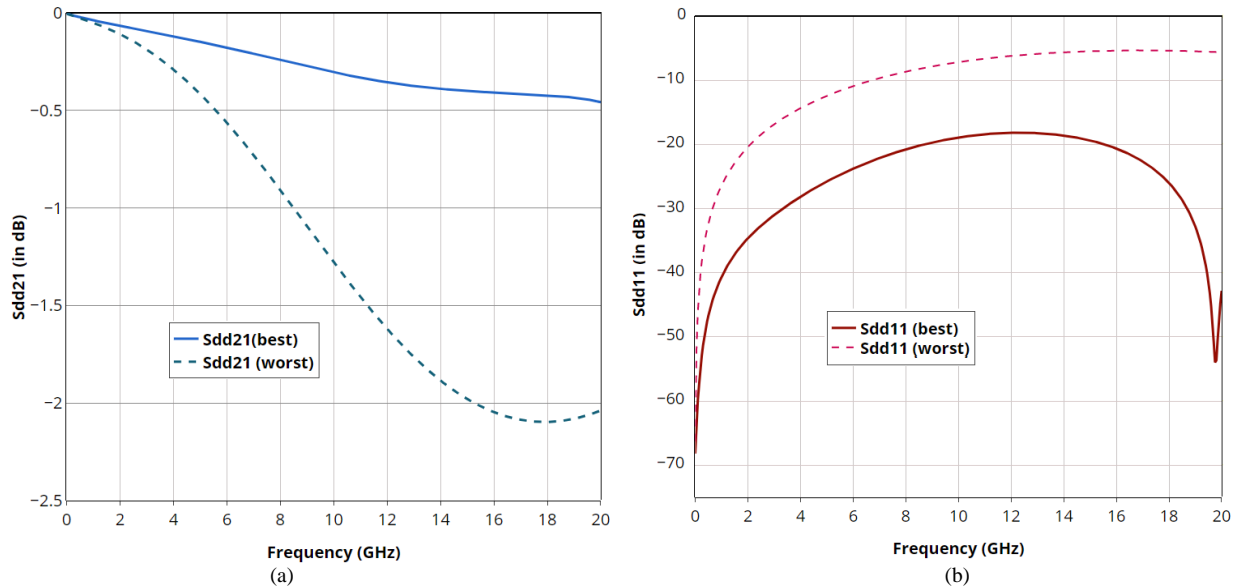


Figure 7. Differential mode parameters of the via in best and worst cases found in CCD (a) Insertion loss, Sdd21; (b) Reflection loss Sdd11

The CCD response surface can provide the insight needed to view the impact parameters in a convenient way. Many response surfaces can be generated by stepping through one variable at a time. The following response surface is one example of such family of response surfaces. It uses via separation of 1.016mm (40 mil):

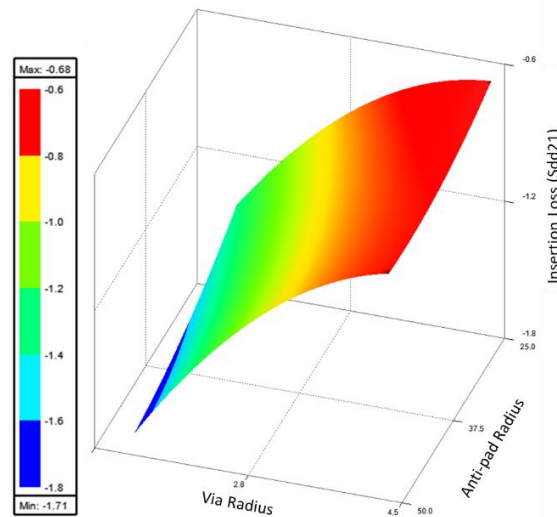


Figure 8. Response surface center composite design for differential mode via. (anti-pad radius and via radius are in mil, and Insertion loss is in dB)

V. CONCLUSION

In this manuscript, a brief summary of Central Composite Design (CCD) and Box-Behnken Design (BBD) methods were presented. Their use in design of vias, operating in differential mode, are illustrated using FEM based

electromagnetic simulation tool. In manufacturing, some intermediate values cannot be picked due to tooling size (e.g. drill bit size). That constraint was not used in this study. If needed, a very close value for via fabrication can be picked. While both methods arrived at similar solutions. However, CCD has more combinations to run compared to BBD. Also, the time cost of CCD was found to be higher than BBD using the same computing resources. In deeper investigation, it was found that BBD had 4 sets of runs to arrive at the results taking an approximate total of 80 minutes. Whereas, CCD created 10 sets of runs, and took approximately 217 minutes. BBD demonstrated faster performance than CCD in this case.

Via transitions are still going to be a major concern among designers of high-speed PCB. In this regard, it was demonstrated how the Design of Experiment can play a vital role in simplifying the workflow and save time by guiding in the right direction. Further studies can be conducted to compare more DOE methods for via transition designs, and more variables can be added in the factorial space.

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